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GRIP PRESSURE AS A MEASURE OF TASK DIFFICULTY IN COMPENSATORY TRACKING TASKS

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THESIS

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IN COMPENSATORY TRACKING TASKS

by

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in Compensatory Tracking Tasks

by

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ABSTRACT

The feasibility of utilizing the grip pressure exerted on a rigid control stick as a measure of tracking task difficulty was investigated. A device was engineered to measure grip pressure independent of control force. A hybrid computer was used to produce the tracking tasks necessary in the research and on-line data computation. Compensatory tracking tasks using K/s, $K/s(s+2)$ and K/s^2 controlled elements provided the difficulty levels, from easiest to most difficult.

Results indicate that grip pressure increases significantly with task difficulty as the operator attempts to reduce his effective time delay. However, grip pressure also appears to be dependent upon the "gain" which a human adopts in a particular tracking task. This gain-related grip pressure may not be related to task difficulty.

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ACKNOWLEDGEMENT

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I. INTRODUCTION

A. BACKGROUND

During an experimental study involving compensatory tracking tasks [Ref. 1] it was noted, but not reported, that the test subjects tended to grip the control manipulator tighter as the task difficulty increased. Smith, [Ref. 2] designed a prototype manipulator which could not only produce the electrical outputs necessary to control a system in a tracking task but could simultaneously measure operator grip pressure. Although Smith's device was hampered by poor signal-to-noise ratios in the grip pressure sensing channels, his results tended to confirm the phenomena noted in the experiments in reference 1.

The apparent relation between grip pressure or neuromuscular tension and task difficulty has been alluded to in the literature. McRuer and Jex [Ref. 3] state that the human pilot can increase the system phase margin and thus improve the stability of a system which may be difficult to control by tightening his grip on the control stick. Magdaleno and McRuer [Ref. 4] first documented the fact that increased neuromuscular tension is accompanied by a reduction in human operator "effective time delay" in tracking tasks. Such a reduction in time delay is synonymous with the increased phase margin mentioned above.

Reference 5 states that average grip pressure is a good measure of increased neuromuscular tension during tracking. Thus, it is

hypothesized here that average grip pressure may be a useful measure of tracking task difficulty, i.e., the necessity of increasing system phase margin. As such, grip pressure may be a useful tool for flight simulation work.

B. OBJECTIVES

The objectives of this research were to:

1. Engineer a grip pressure measurement device which would be highly sensitive, simple in its design and universal in its possible applications.

2. Verify the findings of reference 2 with the possibility that average grip pressure could be used as an indication of task difficulty.

II. THEORY

The problem in previous attempts to measure grip pressure independently of control force was that the device used was too insensitive. Smith [Ref. 2] used rosette strain gauges in the grip of a plexiglass control stick. Because of the problems encountered, he recommended that a more sophisticated control stick, with better amplifiers and shielding, be fabricated. Rather than using the same basic method of detection and merely upgrading the components, a new method of detection was considered here.

The vector sum of forces which a subject exerts on a control stick in a single axis control task can be thought of as the sum of two vectors; one representing the vector sum of the control force and grip force, another in the opposite direction, representing grip force alone. As shown in figure 1, the larger force is the combination of grip force and control force while the smaller force is grip force alone. This simplified representation amounts to a definition of grip force and is the basis of the grip "pressure" measurement technique to be described. Hence, the magnitude of either of the equal but opposite grip forces is defined herein as grip "pressure".

To detect the forces acting on opposite sides of a control stick, a device consisting basically of two rectangular deflection plates was engineered. At the bottom of each plate a full strain gage bridge was

mounted. These plates were attached to a four-inch isometric control stick with a ball top. Figure 2 shows the deflection plates and attached strain gages. The strain gages were SR-4, 120 ohm type, with a gain factor of approximately two. Each bridge circuit output was connected to an operational amplifier with a gain of 1000. The amplifiers were Analog Devices Inc. model 605L. Figure 3 shows the circuit diagram of the deflection plate bridge circuit, amplifier, and associated power supplies.

The deflection plates and attaching plates were machined of extruded aluminum alloy with a modulus of elasticity of approximately 10,000,000 psi. The dimensions of the deflection plates were sized such that there would be adequate strain on the strain gages to give an easily detectable signal, without excessive bending in the plates. Coupled with physical constraints to ensure a comfortable grip size, the final dimensions were those shown in figure 2. It was considered that the maximum deflection of the ends of the deflection plates should be no more than 1/32 of an inch for an applied force of 20 pounds. With this guideline and using a plate thickness of 1/8-inch and a base width of one inch, a plate length of two inches was computed. The equations used were:

$$\text{Deflection } (\delta) = PL^3/3EI$$

where:	P	=	Applied force (lbs)
	L	=	Moment arm length (in)
	E	=	Modulus of elasticity (psi)
	I	=	Moment of inertia (in^4) = $BH^3/12$
	B	=	Base width (in)
	H	=	Thickness (in)

$\delta = 4PL^3/EBH^3$

$L^3 = \delta EBH^3/4P$

With: δ = 1/32 in
E = 10,000,000 psi
B = 1 in
H = 1/8 in
P = 20 lbs

$L^3 = 7.63\ in^3 = (1.97\ in)^3$

L = 2 in

With the deflection plate dimensions specified, the output voltage of the bridge circuits was predicted using the following equations:

Bending stress (σ) = Mc/I

where:
M = Moment applied (lb-in) = PL
P = Force applied (lb)
L = Moment arm length to strain gages (in)
c = Half the plate thickness (in) = H/2
H = Thickness (in)
I = Moment of inertia (in^4) = $BH^3/12$
B = Base width (in)

Strain (ϵ) = σ/E

where:
σ = Bending stress (psi)
E = Modulus of Elasticity (psi)

$\epsilon = Mc/IE = 6PL/EBH^2$ (after some substitution)

Voltage output of full bridge with four active strain gages is given by:

$Vo = \epsilon VsFG$

where:
ϵ = Strain (in/in)
Vs = Bridge supply voltage
F = Strain gage factor
G = Amplifier gain

$Vo = 6PLVsFG/EBH^2$

For deflection plate dimensions:

$B = 1$ in
$L = 2$ in
$H = 1/8$ in

And other constants:

$E = 10{,}000{,}000$ psi
$V_s = 4$ volts
$F = 2$
$G = 1000$
$P = 1$ lb

$V_o = .6144$ volts/lb

With these predicted values of deflection and output voltage, the grip pressure measuring device was assembled and calibrated. The assembled device is shown in figure 4 with grip handles attached to the deflection plates. The grip handles were machined out of a strong epoxy material. For calibration, the device was clamped to a table in a horizontal position. The amplifiers were zeroed to within plus or minus two millivolts and then the bridge circuits were balanced to a point where only 0.2 millivolts of noise remained. This was done prior to placing the stick in the horizontal. A basket was fashioned and hung on the grip such that the moment arm with respect to the strain gages was approximately two inches. Weights were gradually added to the basket and output voltage was recorded. Up to five pounds of weight were added and then gradually removed to check for any hysteresis effects. The device was turned over and the other plate was calibrated in the same manner. Figure 5 shows the calibration

curve produced. Both deflection plates were nearly identical in their outputs and showed no hysteresis effects. The offset at the zero force position was due to the device's own cantilever weight which produced the slight deflection noted. The outputs of the plates were completely independent. The calibration agreed very closely with predicted output values. In particular, at a force of 2.2 pounds the output was approximately 1.34 volts (considering the 60 millivolt offset at zero force), compared to a predicted value of 1.35 volts (0.6144 volts/lb times 2.2 lbs). Thus, there was a difference of 0.75%.

Although the dimensions of this device were basically restricted so that it could be used on a particular control stick, almost any shape could be fabricated for different applications. The device described here proved to be highly sensitive, linear, and able to detect and differentiate the fore and aft forces necessary in computing grip pressure as described earlier.

III. EXPERIMENTAL PROCEDURE

A. EQUIPMENT

The equipment used in the experiment consisted of:

1. Grip pressure measurement device mounted on a rigid control stick and associated equipment.

2. Analog Computer

3. Digital Computer

1. Grip Pressure Measurement Device/Rigid Control Stick

The grip pressure measurement device described earlier was mounted on an isometric or rigid force stick about four inches long, and the whole assembly was mounted on a chair. [Figure 6] Associated equipment consisted of two signal generators, two low-pass filters, a dual-axis cathode-ray tube (CRT) and an eight pen strip-chart recorder. One of the signal generators powered the rigid control stick, and the other provided a steady horizontal line on the CRT display. The low pass filters were used for the input to the vertical and horizontal plates of the display to remove high frequency noise originating in the analog computer. The strip-chart recorder provided time histories of the grip pressure during tracking runs.

2. Analog Computer/Digital Computer

Central to the entire experiment was the CI5000 Analog Computer, which generated the tracking tasks and the SDS9300 Digital

Computer which controlled the operation of the analog computer and provided on-line data reduction. Thanks to previous research by Lieutenant Walter Michael Teichgraber [Ref. 6], a general analog patchboard and associated computer program were available that completely mechanized the tracking tasks and provided on-line data reduction. The computer program was modified to include statements for computing grip pressure at any particular instant and a subroutine to determine the average grip pressure over the length of a tracking run. As mentioned previously, the output from the grip pressure device was a voltage signal from each deflection plate, the smaller of the two signals being the grip pressure (force) exerted. This comparison of signals was done using the hybrid facilities of the analog and digital computers. By using the trunk lines coupling the computers, analog signals from the deflection plates were converted into digital signals, sampled 60 times a second, and compared in the computer program using a group of "IF" statements; the smaller signal being labeled the grip pressure. This grip pressure was integrated in the digital computer over the length of the subcritical task runs to compute "average grip pressure." The digital grip pressure signal was also converted back into an analog signal for recording on the strip-chart recorder.

For a thorough description of the hybrid operations used, the computer program used, and the operating instructions for Lt. Teichgraber's hybrid set-up, see reference 6.

B. PROCEDURE

1. Equipment Preparation

All the equipment described earlier was located in Room 500 of Spanagel Hall at the U. S. Naval Postgraduate School. Prior to a test subject's arrival, all equipment was readied according to the instructions in reference 6. In general the following steps were taken in chronological order:

a. Analog patchboards (#19) were installed in the analog computer. Connections were made between the analog patchboard and the filters, signal generators and the CRT display unit. The analog computer was turned on and placed in a mode for digital computer control. The strip chart recorder was turned on.

b. The digital computer was readied according to its own instructions manual. The necessary data card was punched [Ref. 6, p. 79-80], and then the hybrid program deck was read into the computer for compilation and execution. The timing switch for the digital computer was checked to ensure that it was in the "internal mode."

c. As the program was being compiled in the computer, the desk and control stick assembly were placed in front of the CRT display unit. The desk was placed in such a way that a nominal 20-inch eye-to-display distance was maintained for standardization with prior research. The grip pressure measurement device output leads were inserted into the analog computer patchboard for hybrid utilization as mentioned

previously. The output leads consisted of the two active deflection plate leads and a common ground lead. To stabilize the grip pressure signals the active leads were inserted into the input jacks of operational amplifiers prior to connection with the trunk lines of the computer. The power supply for the grip pressure measurement device was plugged in and turned on so that the bridge circuits could warm up properly prior to taking grip pressure readings.

d. After the program was compiled and data card read, the appropriate codes were entered in the digital computer for the type of tracking task desired. The control stick was then calibrated according to the instructions of reference 6, p. 80-82. The control sensitivity was kept at 1.75 in/lb for the K/s controlled element and 5.83 in/sec/lb for the K/s(s+2) and K/s^2 controlled elements. These control sensitivities are equivalent to the 1.0 cm/Newton and 3.33 cm/sec/Newton sensitivities used in prior research with cross adaptive tracking experiments conducted in reference 7. These sensitivities represent the amount of deflection of the horizontal line on the CRT screen per unit of force on the control stick with a controlled element of unity. The calibration completed, the computer asked for the number of runs desired. The parameters KRUN and LRUN were entered depending on what number was desired to indicate the upcoming run and how many runs of the particular tracking task were desired respectively.

e. Finally, the amplifiers and bridge circuits of the grip pressure measurement device were zero balanced to within plus or minus one millivolt. With this completed, all systems were ready for subject testing.

2. <u>Subject Testing</u>

Three subjects were used in this research: the author; the author's wife and a naval aviator. The author (Subject JH) had no previous tracking experience, but was a naval flight officer and private pilot. The author's wife (Subject NH) had no tracking experience and no aviation experience. Subject (DW) had no prior tracking experience, but was an experienced Navy pilot.

All subjects other than the author were briefed on the experiment using a short written set of instructions. Each subject completed a series of compensatory tracking tasks with three so-called "critical" controlled elements and three stable controlled elements (see Tables I and II and Fig. 7). The display area for tracking was a four inch square on the CRT display unit and a bright green horizontal line approximately 1/16 of an inch wide was displayed on the CRT. Subjects started with the first order critical controlled element, then tracked with the K/s stable element. Next, the "1.5" order critical controlled element followed by the K/s(s+2) was used. Finally, the second order critical element was utilized, followed by the K/s^2 element. For each critical task, runs were repeated until it was

felt that the subject's critical instability level (λ Crit) was reached. Runs with the K/s, K/s(s+2), and K/s^2 dynamics were continued until the subjects learning curve (RMS tracking error versus run number) leveled out. See figure 8 for a typical learning curve example. Grip pressures were measured and recorded after significant learning was complete.

a. Critical Task Runs

The reader is referred to reference 5 for information on the critical tracking tasks. These tasks were included in this study to verify the results of reference 2 in attempting to determine intra-run variation in grip pressure with task difficulty.

The initial value of the instability level was set at 1.0 rad/sec. The digital computer increased the instability level at a constant rate of 0.1 rad/sec^2 until the critical instability level was reached, where the subject could no longer keep the horizontal line within the four inch square on the CRT. The analog computer circuits for first, "1.5" and second order critical tasks are shown in reference 6 on pages 48, 49 and 50 respectively.

b. Stable Task Runs

The analog computer circuits used for the K/s, K/s(s+2) and K/s^2 controlled elements are shown in reference 6 on pages 57, 58 and 59 respectively, with the exception that the noise generator circuit was not used. The input presented to the subject was the sum of five

sine waves generated in the digital computer. This input had been recommended in reference 6 and was incorporated in this research (see Table II). All runs were of ninety seconds duration. This was long enough for accurate root-mean-square error calculations and average grip pressure calculations, but not so long that subject fatigue would set in. After the subject's learning curve leveled out to a fairly constant RMS error, ten to twenty more runs were performed so that a good average grip pressure could be established. As reference 7 shows, the K/s, $K/s(s+2)$ and K/s^2 controlled elements constitute increasingly difficult control tasks for the subjects. This is due to the fact that the elements require increasing amounts of lead equalization by the subject.

3. <u>Data Analysis</u>

The majority of the data analysis was done by the digital computer. In critical task runs, the computer calculated the critical instability level reached for each run. In the stable task runs the computer calculated the mean input, RMS input, mean error and RMS error. RMS error was used as the measure of performance to indicate when the subject's learning curve had leveled out. The computer also calculated the average grip pressure over the length of the stable task runs. This was the primary measurement of this research. These computations were checked occasionally with strip-chart recordings of the grip pressure. Figure 9 shows a representative strip-chart

recording of grip pressure versus time. Off-line data reduction included computing average critical instability levels for a set of critical task runs, and the average grip pressure and standard deviation for a set of stable task runs.

IV. RESULTS

The results of the testing, presented in figures 10, 11 and 12 confirm the results of reference 2. Increased task difficulty does produce increased grip pressure. The figures show average grip pressure and respective standard deviations for the three stable controlled elements. Although the subjects had different ranges of grip pressure for the three controlled elements investigated, the trend was the same for all. Average grip pressure was calculated in the following manner. Once it was ascertained that a test subject's RMS error performance had leveled-out, approximately twenty more runs were recorded. Out of these twenty, average grip pressure readings for the ten runs with the lowest root-mean-square error were used to calculate the overall average grip pressures shown in figures 10, 11 and 12. Figures 13, 14 and 15 present the root-mean-square error results for the ten best runs.

Several attempts were made to find a normalizing value for average grip pressure. The method used in reference 2 was to use the subject's maximum grip pressure exertable on the control stick. This method was unsatisfactory for this experiment because the measurement device could be deflected to its limits by all test subjects involved. Another method was also considered which attempted to use

grip pressure readings from first order critical task tracking runs performed by the test subjects. Reference 2 described the build-up and final peak of grip pressure exhibited by test subjects when performing critical tracking tasks. This behavior was also observed in this research. It was hoped that an average peak value of grip pressure could be used as a normalizing value. This method was ineffective because the grip pressure sensing device was so sensitive that peak values recorded were too erratic to be used as a normalizing value. Thus direct average grip pressure readings were presented in figures 10, 11 and 12.

Figure 16 illustrates an interesting result of the experimentation. Initially the control stick sensitivity was set at 1.75 in/lb for the K/s controlled element and 5.83 in/sec/lb for the K/s(s+2) and K/s^2 controlled elements. The results of the K/s runs showed little or no difference in grip pressure compared with the K/s(s+2) runs. The control stick sensitivity for the K/s controlled element was then changed to 5.83 in/lb so that the sensitivity was the same for all controlled elements. Figure 16 shows the results of this change in gain for the K/s element. Grip pressure decreased considerably with the increase in control stick sensitivity.

The dependence of grip pressure on controlled element or control stick gain (sensitivity) is probably due to the fact that neuromuscular tension and hence, grip pressure are very dependent upon the "gain"

which the subject adopts in steady state tracking. The low gain K/s element required a higher pilot gain and hence grip pressure than did the high gain K/s element.

which the subject adopts an steady state tracking. The low gain K/s element required a higher pilot gain and better grip pressure than did the high gain K/s element.

V. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were drawn from this research:

1. Average grip pressure shows some potential for measuring task difficulty and may be a valuable tool in simulator work as regards training and evaluation of human operators.

2. The dependence of grip pressure on both controlled element gain and task difficulty raises some obvious problems if grip pressure is to be used as a measure of task difficulty.

3. The grip pressure device and method of grip pressure measurement used in this research offers many advantages over other devices and techniques used to measure workload including simplicity of design, cost of installation, reliability, sensitivity and universality of application.

The following recommendations are made with respect to future research:

1. Continue testing with more subjects and more runs to determine whether there may be a universal average grip pressure gradient related to task difficulty.

2. Fabricate new deflection plates out of steel for the grip pressure device used in this research. Construct contoured finger grips to fit on the deflection plates, so that the same grip position is

is taken on the stick at all times. Also find a new chair on which to mount the control stick and grip pressure assembly, with the objective of having the subjects forearm more horizontal and control stick canted slightly forward. This will alleviate the problem subjects found in putting back pressure on the stick. The desk sloped slightly upward and the control stick was tilted back from the vertical.

3. Design new detection devices for different applications. The size of the deflection plates seem restricted by the size of the strain gages required, but different materials can be used to produce whatever voltage output and deflection desired.

4. Fabricate a grip pressure measurement device that can be utilized with the carrier landing simulator and cockpit simulator in the Electrical Engineering Computer Lab at the U. S. Naval Postgraduate School.

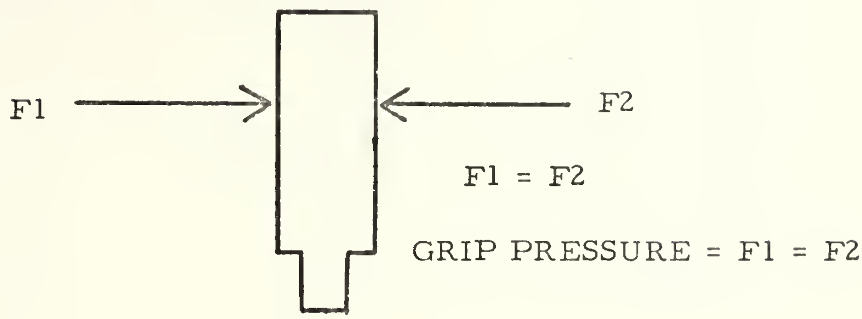
5. Investigate the dependence of average grip pressure upon control stick sensitivity or controlled element gain for a range of stick sensitivities with a single controlled element.

6. To establish the sensitivity of grip pressure as a measure of task difficulty, conduct experiments utilizing unstable subcritical tracking tasks with incremental values of the critical instability level (λ Crit) as the unstable root. This research would show to what extent grip pressure can detect small differences in task difficulty. With slight modifications the mechanized hybrid system used in this research could also be used for the above recommended research.

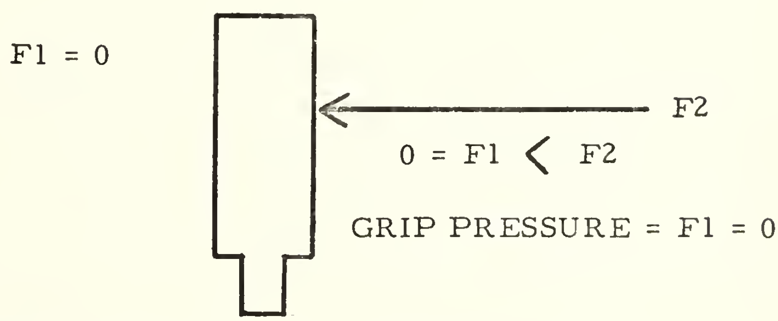
7. Procure or fabricate a solid state device (possibly a miniature-chip computer) that can perform the evaluation function of determining the smaller of two signals and passing it on, as was performed by the digital computer in this research. This device could be placed directly after the amplifiers in figure 3 with the output being grip pressure. Thus a digital computer would not be necessary to detect grip pressure. The final product would be a device that could be used at installations and facilities where hybrid computers are not available.

VI. FIGURES

NO CONTROL FORCE - GRIP PRESSURE ONLY



NO GRIP PRESSURE - CONTROL FORCE ONLY



GRIP PRESSURE AND CONTROL FORCE

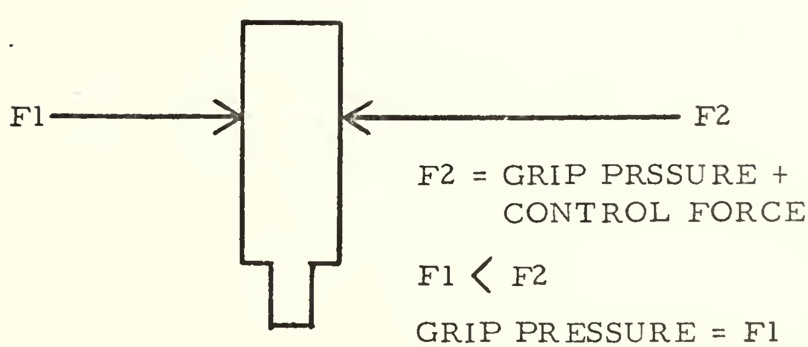


Figure 1. Grip Pressure as The Smaller of Two Forces

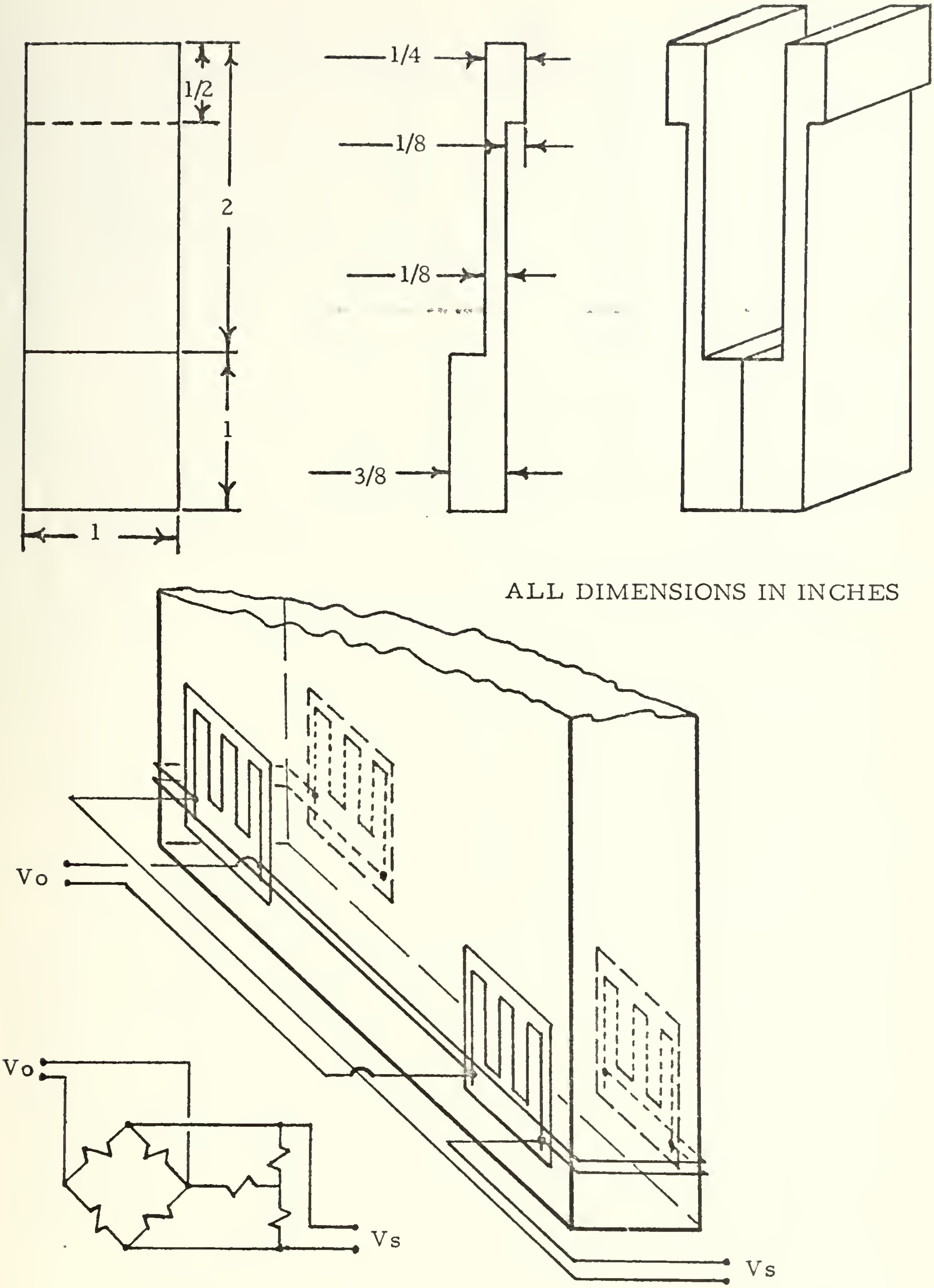
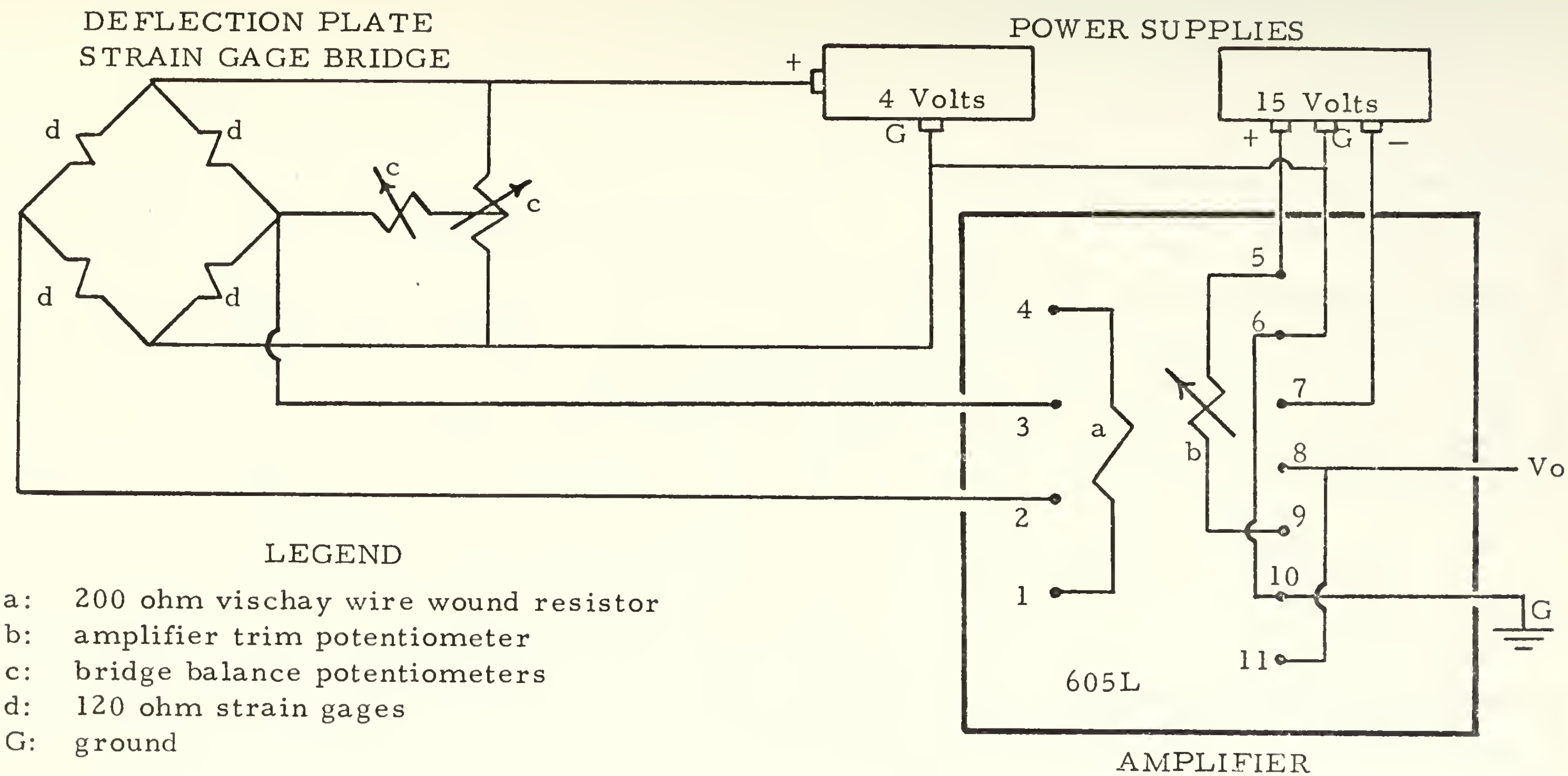


Figure 2. Deflection Plates and Strain Gauge Bridge Circuit



LEGEND

a: 200 ohm vischay wire wound resistor
b: amplifier trim potentiometer
c: bridge balance potentiometers
d: 120 ohm strain gages
G: ground

NOTE: The above circuit is for one deflection plate. Both deflection plate circuits are identical. Output voltages Vo are compared in the computer.

Figure 3. Deflection Plate Circuit Diagram

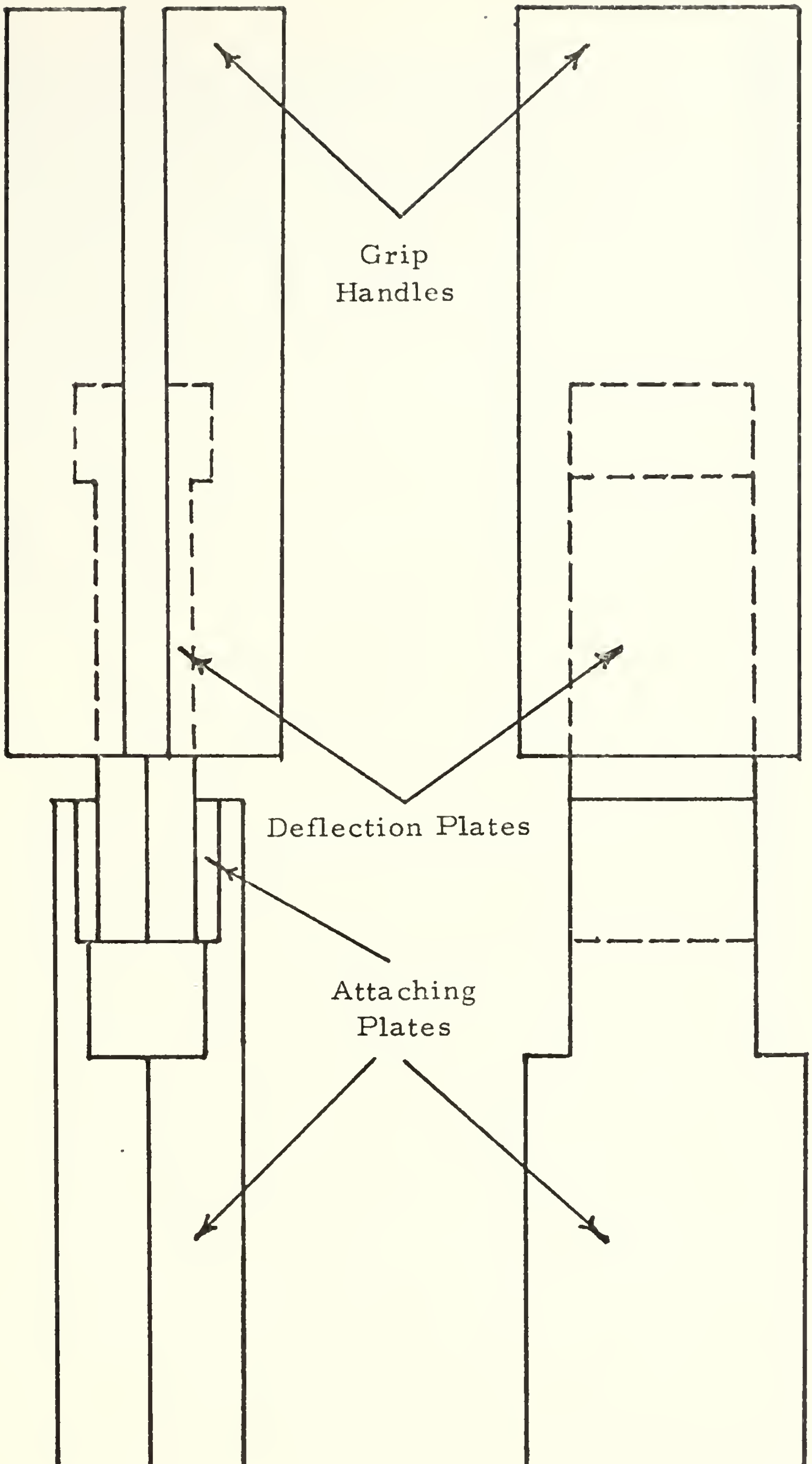


Figure 4. Assembled Grip Pressure Measurement Device

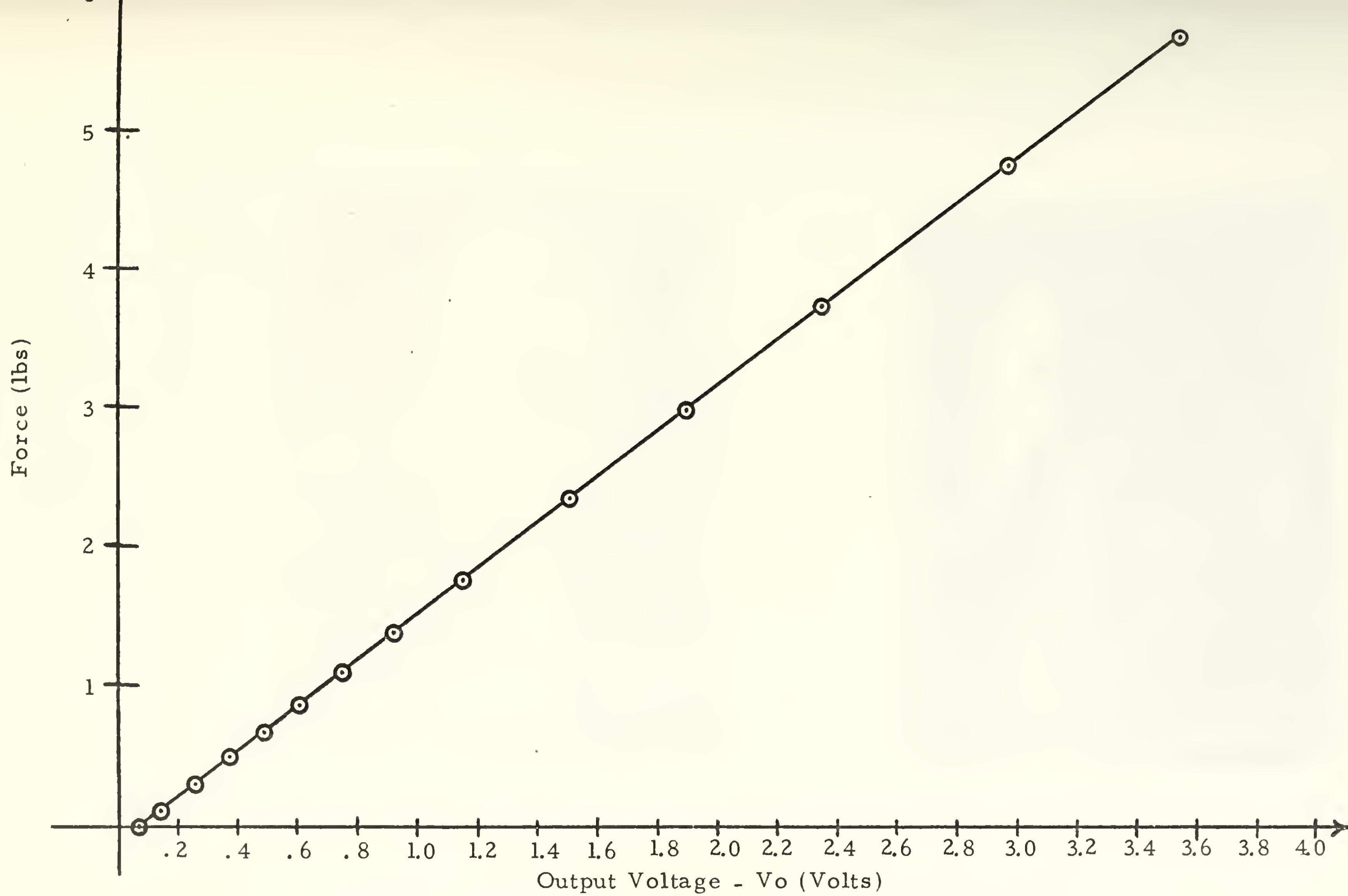
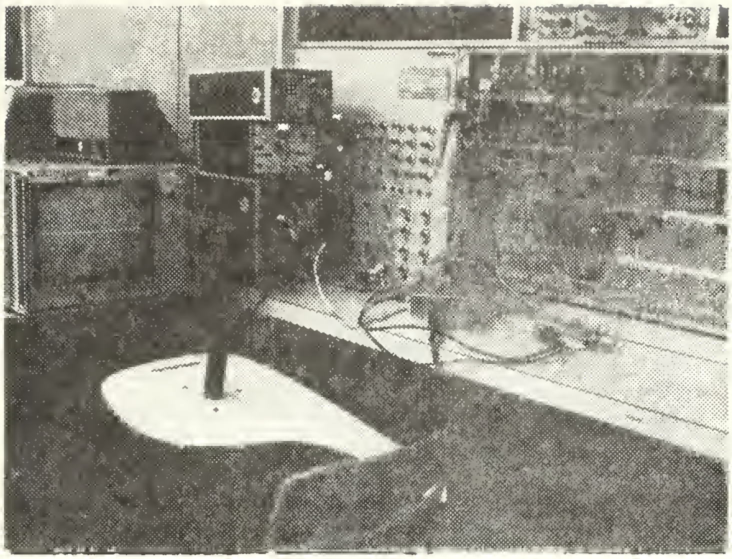
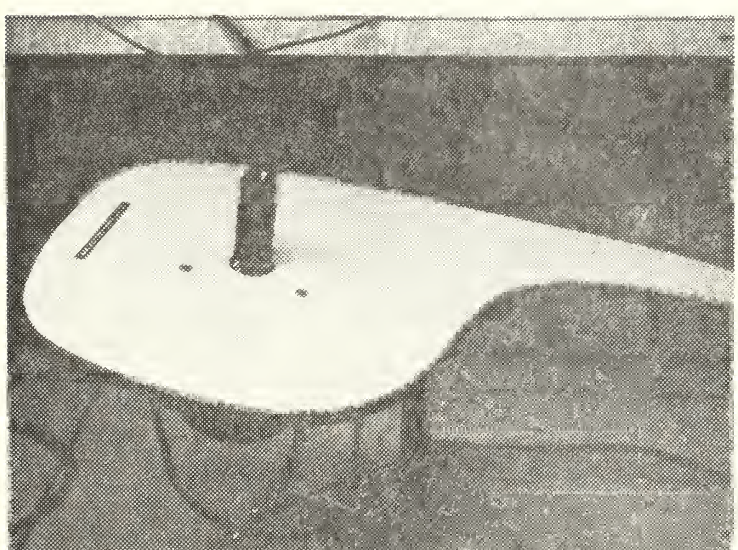


Figure 5. Calibration Curve - Force vs. Output Voltage

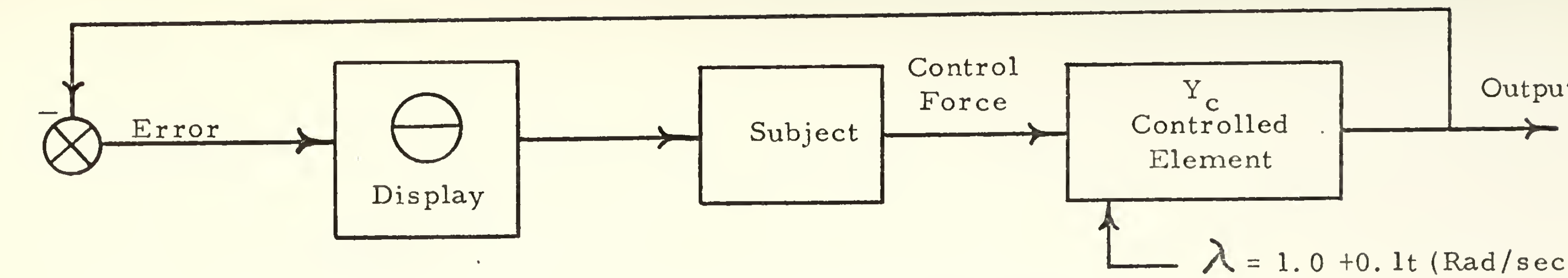


Associated Equipment

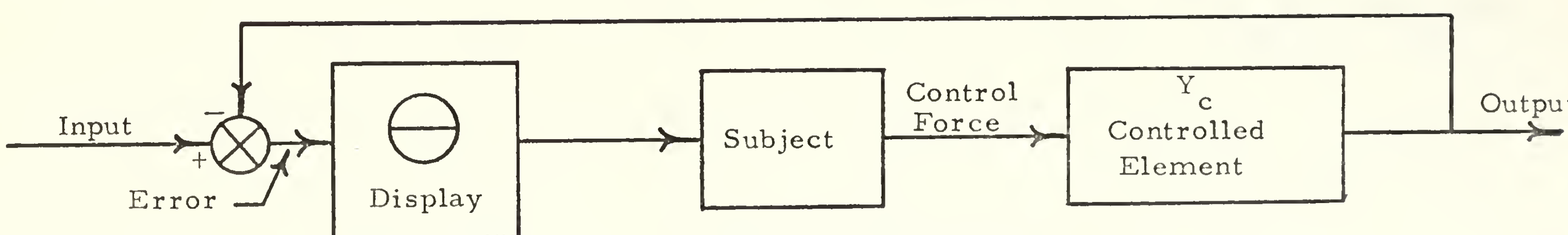


Control Stick/Grip Pressure Device

Figure [illegible]. Control Stick/Grip Pressure Device/Associated Equipment



Single-Axis Critical Task



Single-Axis Stable Task

Figure 7. Block Diagrams of a Single-Axis Critical Task and Stable Task

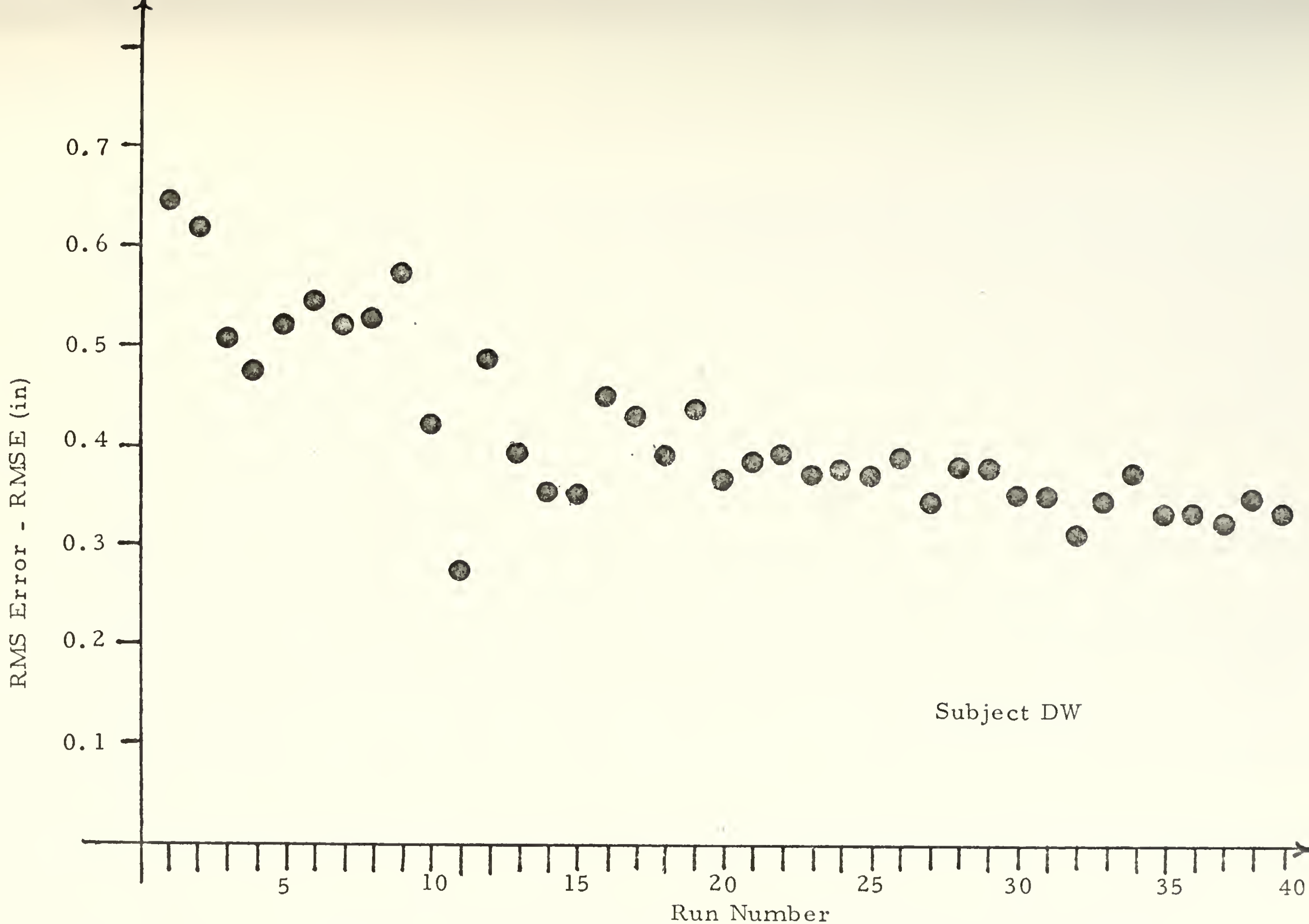
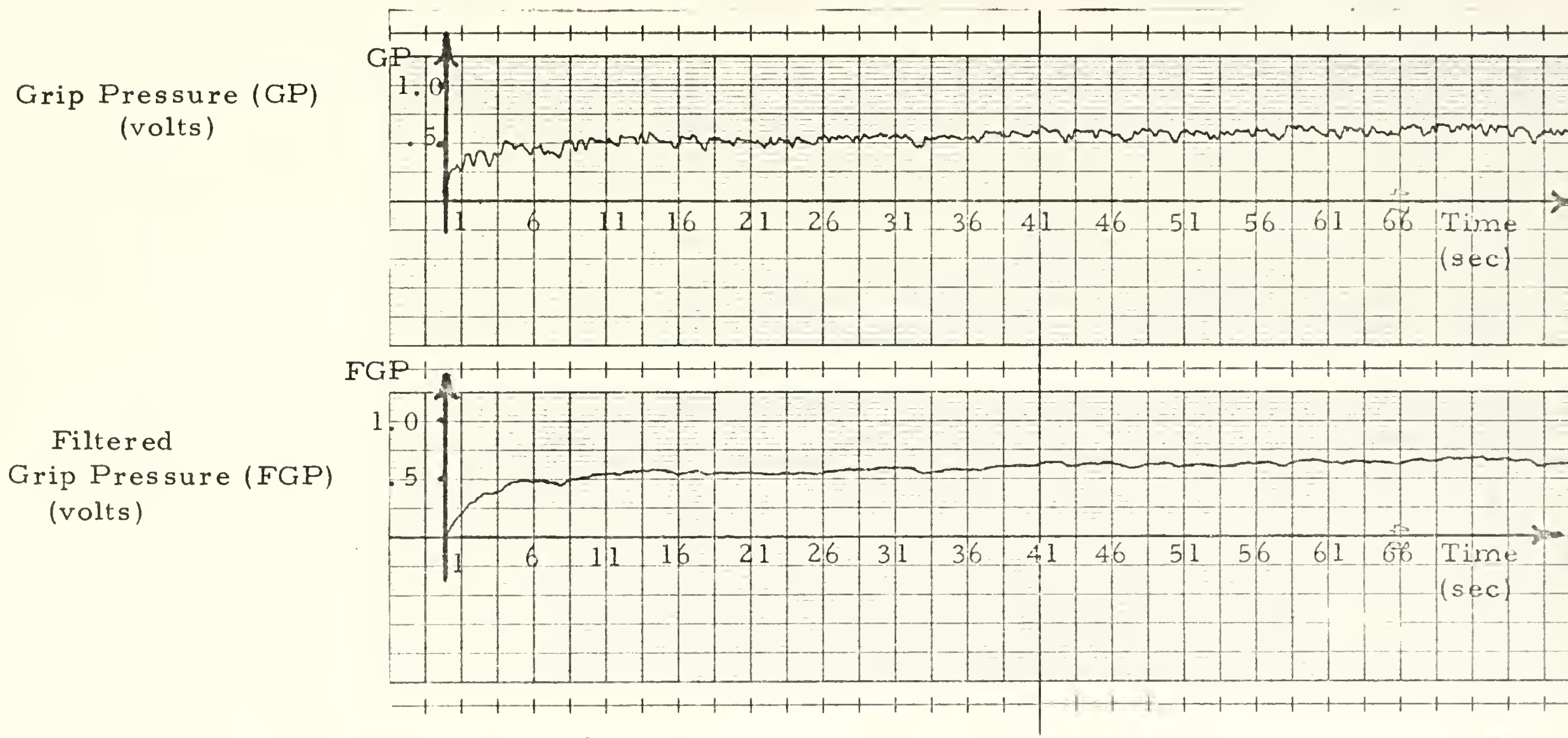


Figure 8. Typical Learning Curve - RMS Error vs Run Number



Note: Computer Calculated Average Grip Pressure Was .60 volts

Figure 9. Strip-Chart Recording - Grip Pressure vs. Time

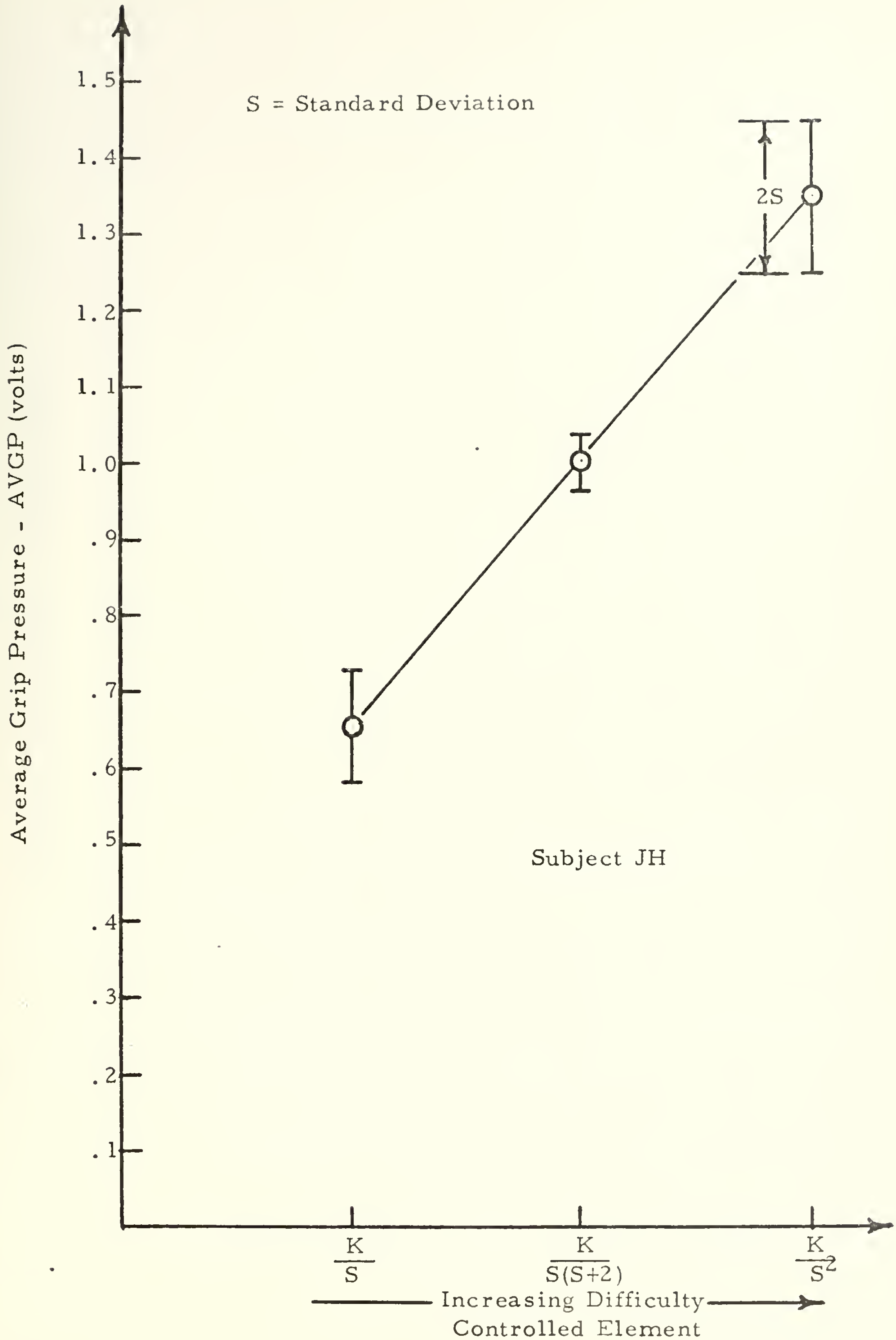


Figure 10. Average Grip Pressure for Three Controlled Elements

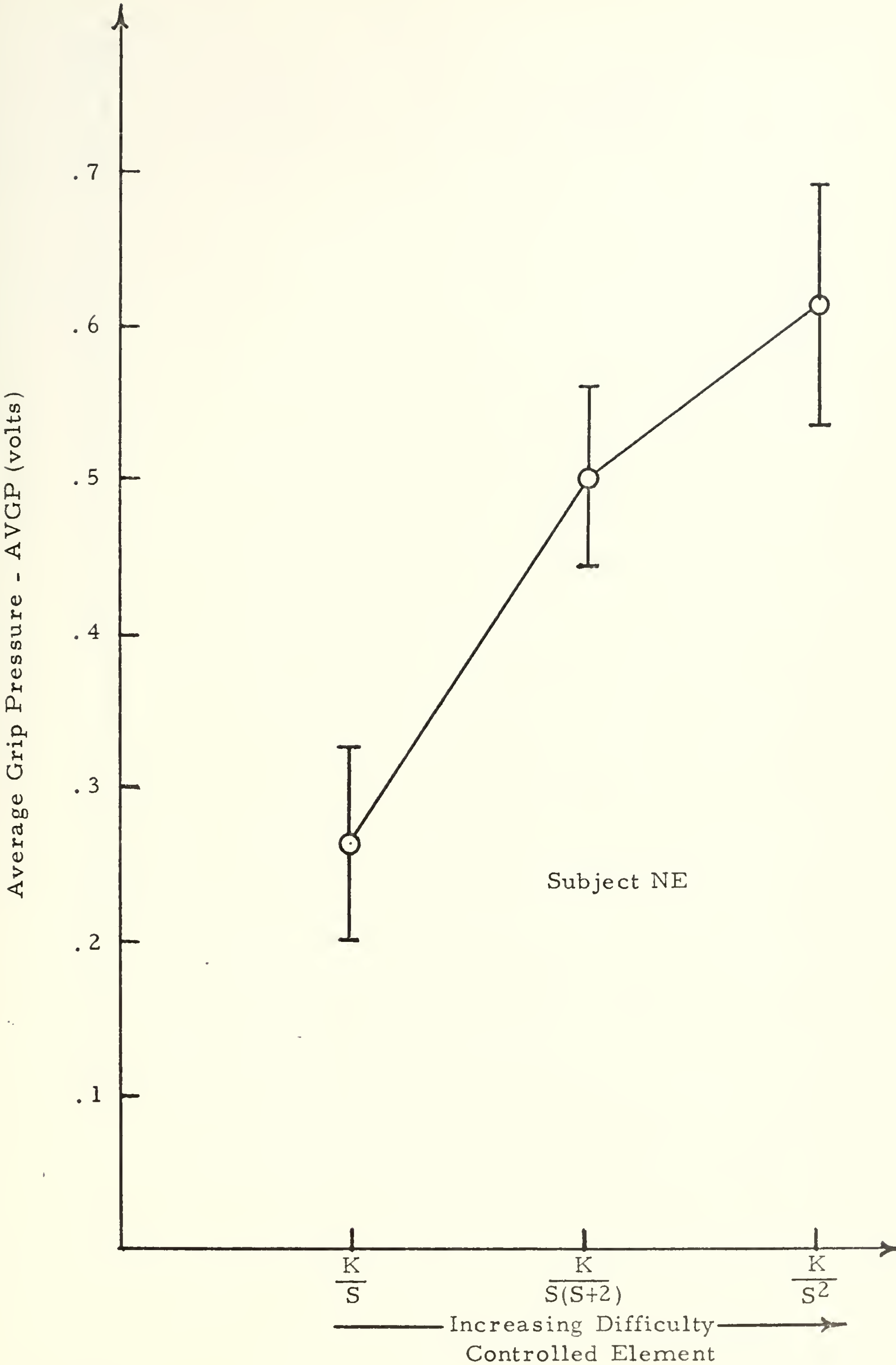


Figure 11. Average Grip Pressure for Three Controlled Elements

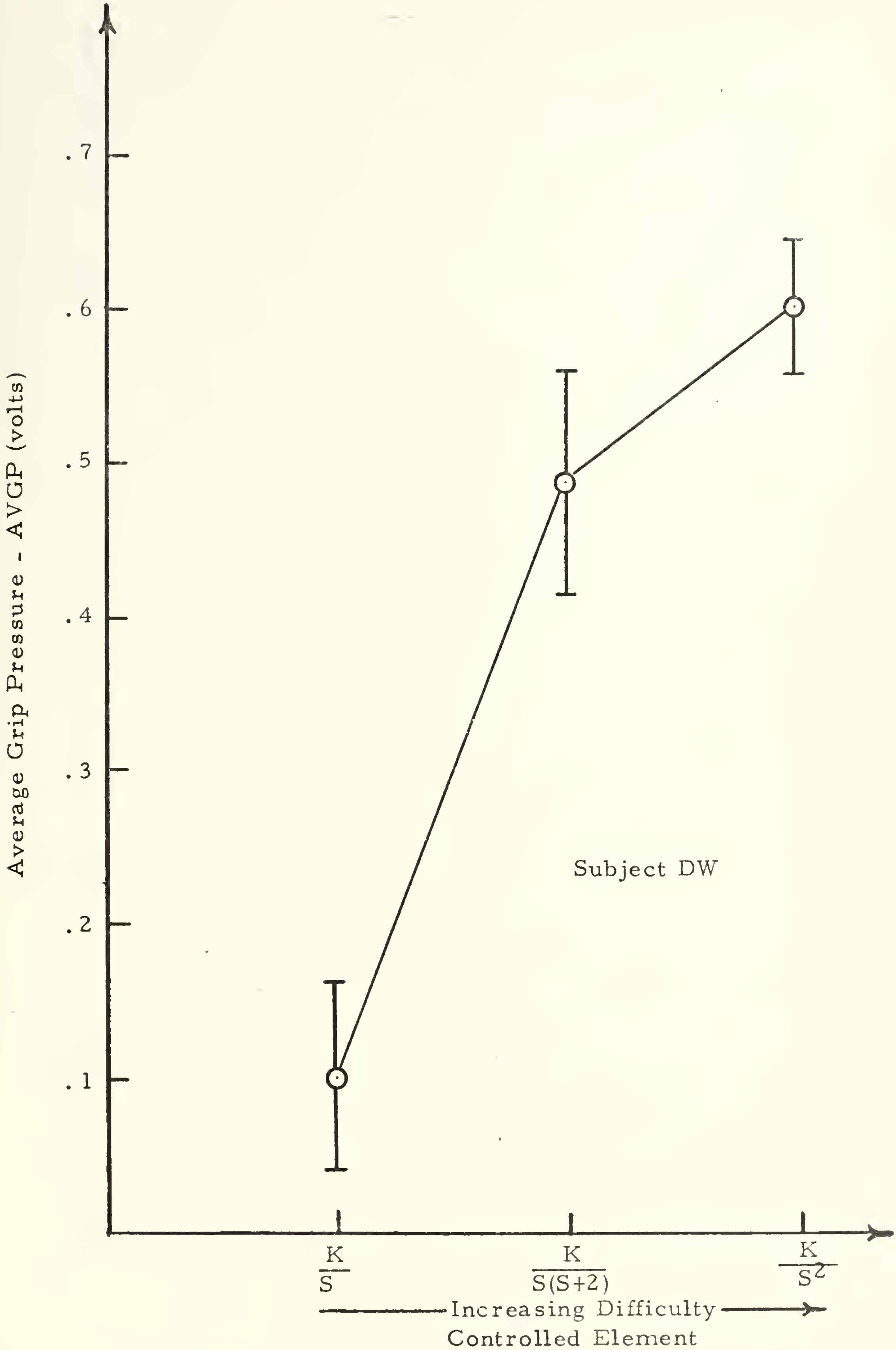


Figure 12. Average Grip Pressure for Three Controlled Elements

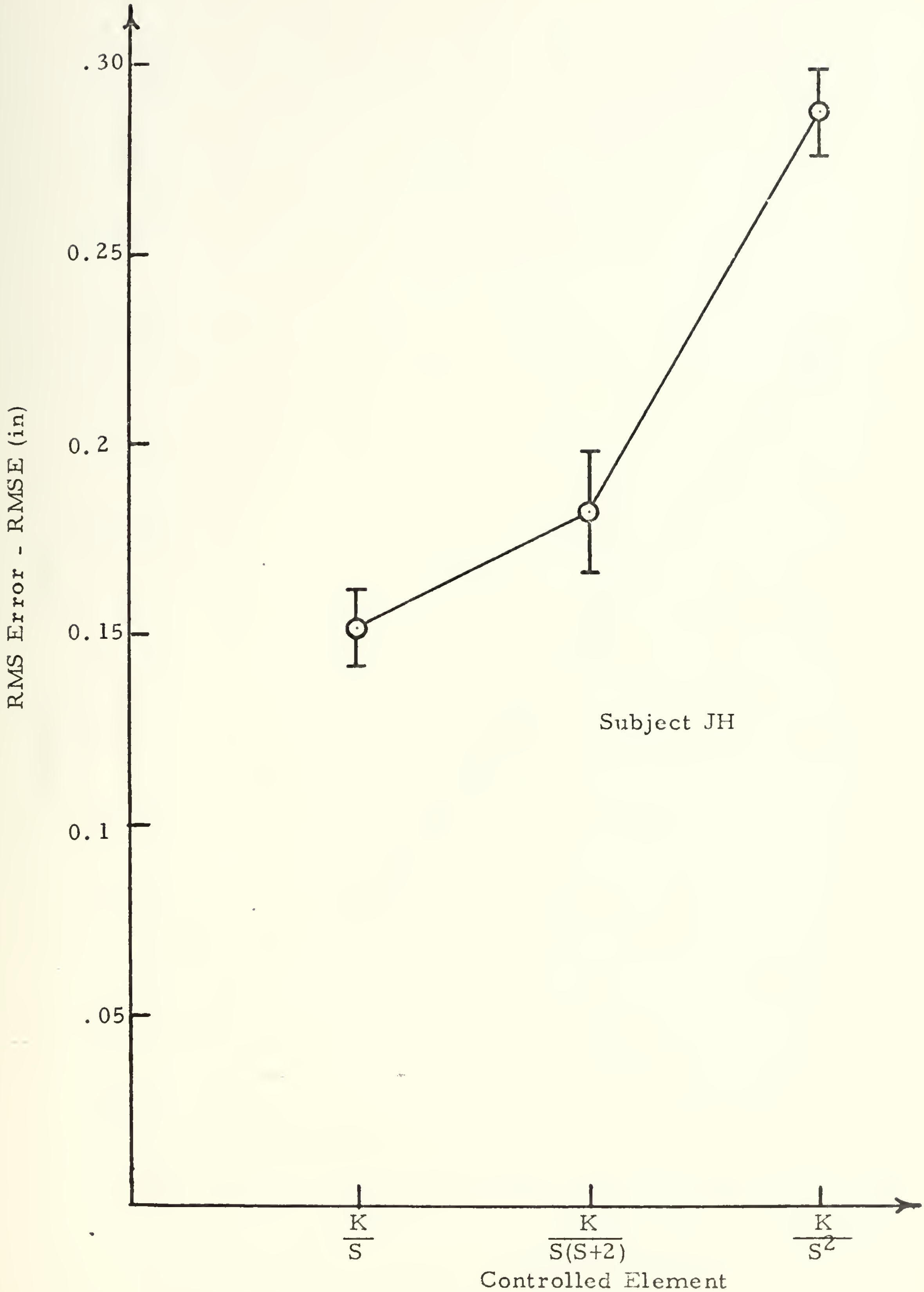


Figure 13. RMS Error for Three Controlled Elements

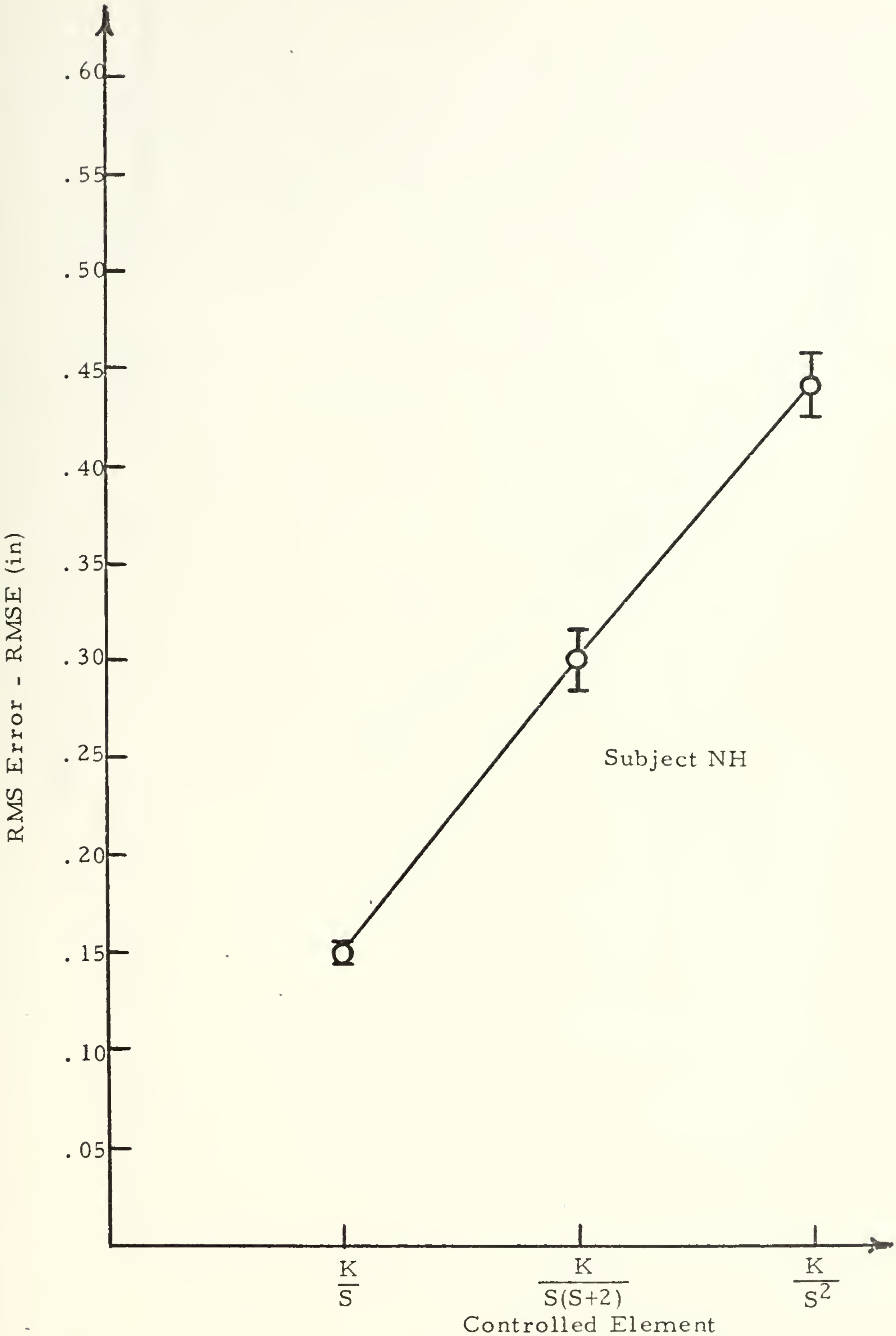


Figure 14. RMS Error for Three Controlled Elements

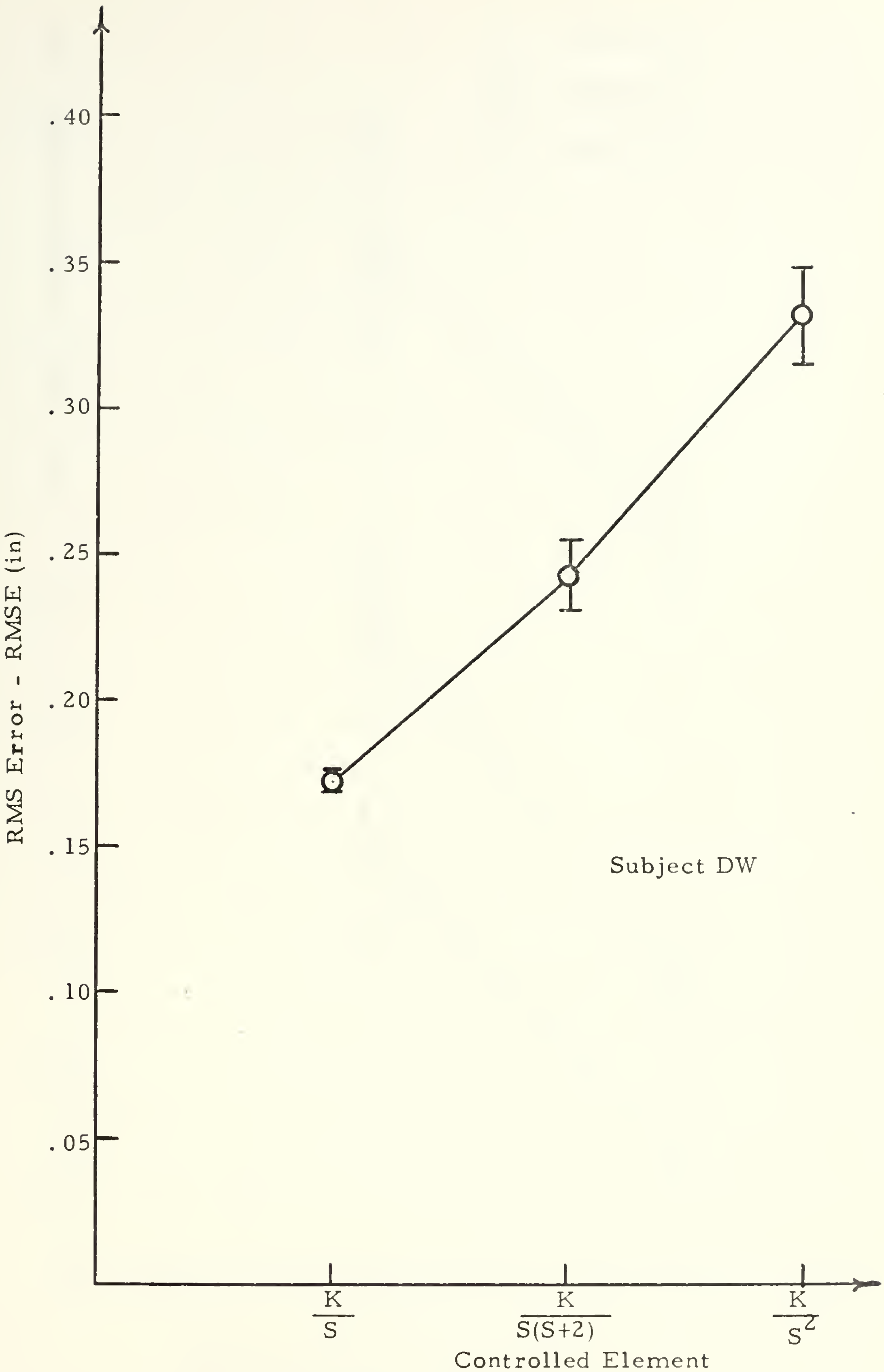


Figure 15. RMS Error for Three Controlled Elements

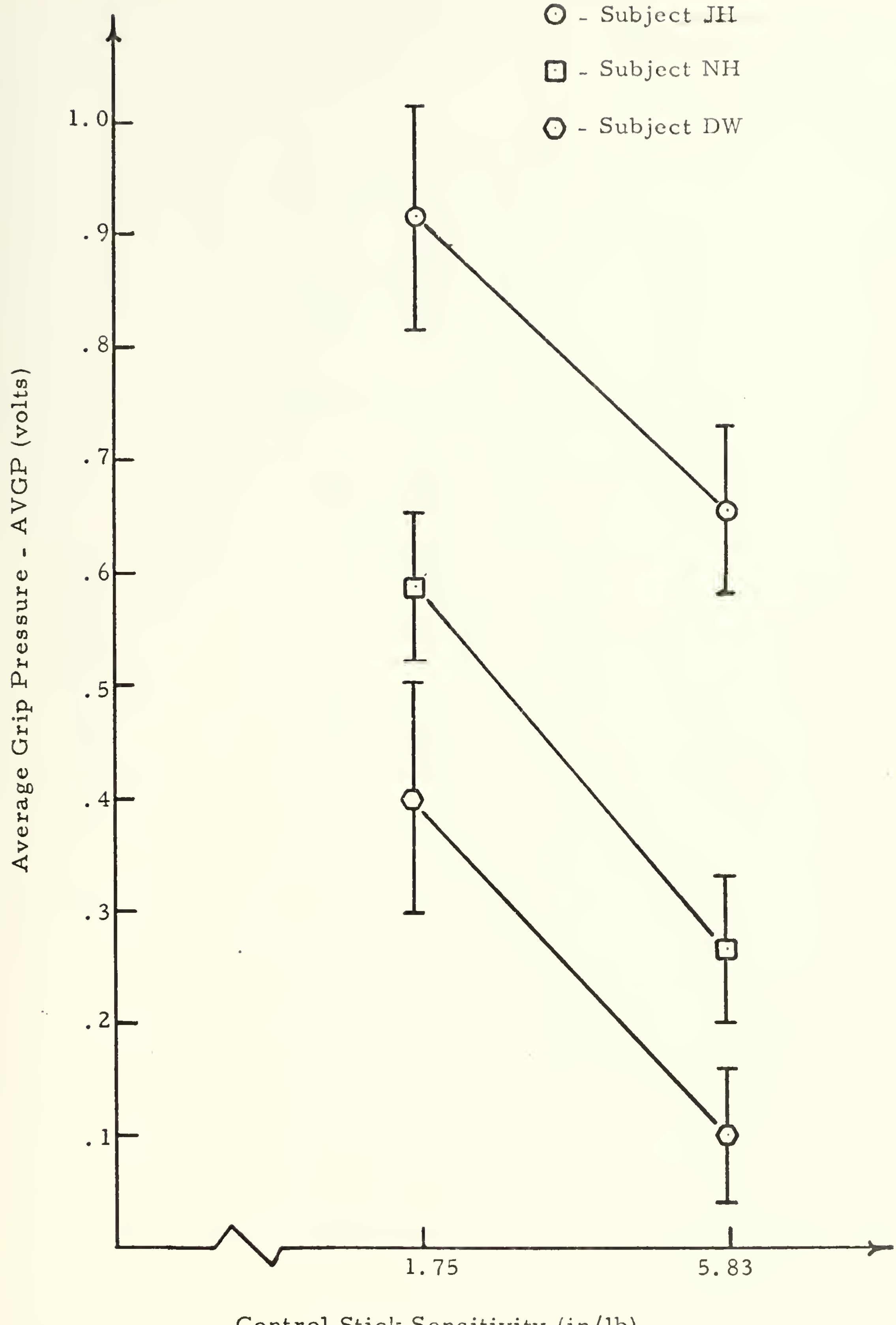


Figure 16. Average Grip Pressure vs Control Stick Sensitivity

VII. TABLES

	1st order	"1.5" order	2nd order
Y_c = Controlled element	$\frac{K\lambda}{S-\lambda}$	$\frac{K\lambda}{(S+2)(S-\lambda)}$	$\frac{K\lambda}{S(S-\lambda)}$
K = Control sensitivity	1.75 in/lb	5.83 in/sec/lb	5.83 in/sec/lb

Table I. Single-Axis Critical Tracking Task Parameters

Y_c = Controlled element	$\frac{K}{S}$	$\frac{K}{S(S+2)}$	$\frac{K}{S^2}$
K = Control sensitivity	1.75 in/lb & 5.83 in/lb	5.83 in/sec/lb	5.83 in/sec/lb
Input	$.39\,[.494 \sin .502t + .460 \sin 1.256t + .204 \sin 3.015t + .0543 \sin 6.282t + .0306 \sin 10.46t]$ (in)		
Input RMS value	.39 (in)		

Table II. Single-Axis Stable Tracking Task Parameters

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The feasibility of utilizing the grip pressure exerted on a rigid control stick as a measure of tracking task difficulty was investigated. A device was engineered to measure grip pressure independent of control force. A hybrid computer was used to produce the tracking tasks necessary in the research and on-line data computation. Compensatory tracking tasks using K/s, $K/s(s+2)$ and K/s^2 controlled elements provided the difficulty levels, from easiest to most difficult.

20.
Results indicate that grip pressure increases significantly with task difficulty as the operator attempts to reduce his effective time delay. However, grip pressure also appears to be dependent upon the "gain" which a human adopts in a particular tracking task. This gain-related grip pressure may not be related to task difficulty.

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Grip pressure as a measure of task difficulty in compensatory tracking tasks.